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Concept Map Value Propagation for Tactical Intelligence

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14. ABSTRACT

Command and control analysts increasingly apply traditionally unassociated concepts to situation understanding. Techniques are needed to tailor knowledge acquisition resource allocation according to probable value of information, both inferring an answer to a question using knowledge at hand and quickening intelligence efforts to fill in gaps. Concept Maps ("Cmaps") are a form of meaningful diagram that represents concepts as nodes, linked by specified relationships. This paper discusses research into methods for negotiating and updating Cmaps by accounting for both nodal data and links. Cmaps provide the flexibility to represent at a meaningful level contemporary tactical knowledge not lending itself to conventional data structures. In some senses Cmapping generalizes the notion of an inference network, a set of propositions organized with rules directing information propagation and combining antecedents to update consequents. We are attempting to develop a mathematical system for organized navigation of a Cmap, driven by expected variability in the value of a datum and cost to get a new value. We use the CmapTools software developed with DoD support at the Institute of Human and Machine Cognition as a structural basis for creating and assessing tactical Cmaps. The paper sets forth Cmap construction, analytical philosophy, and methodology development.

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Concept Map Value Propagation for Tactical Intelligence

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Abstract. Command and control analysts increasingly apply traditionally unassociated concepts to situation understanding. Techniques are needed to tailor knowledge acquisition resource allocation according to probable value of information, both inferring an answer to a question using knowledge at hand and quickening intelligence efforts to fill in gaps. Concept Maps ("Cmaps") are a form of meaningful diagram that represents concepts as nodes, linked by specified relationships. This paper discusses research into methods for negotiating and updating Cmaps by accounting for both nodal data and links. Cmaps provide the flexibility to represent at a meaningful level contemporary tactical knowledge not lending itself to conventional data structures. In some senses Cmapping generalizes the notion of an inference network, a set of propositions organized with rules directing information propagation and combining antecedents to update consequents. We are attempting to develop a mathematical system for organized navigation of a Cmap, driven by expected variability in the value of a datum and cost to get a new value. We use the CmapTools software developed with DoD support at the Institute of Human and Machine Cognition as a structural basis for creating and assessing tactical Cmaps. The paper sets forth Cmap construction, analytical philosophy, and methodology development.

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1. Background and motivation

With the rise of net-centric and effects-based operations in response to asymmetric warfare, analysts have begun to apply traditionally unassociated concepts to situation understanding and intelligence gathering. Dynamic network analysis tools are used to locate and assess networks embedded within large data sets and to establish exploitable patterns. Several such tools exist; however, they are generally inadequate in that analysts spend too much time accomplishing "mechanical" tasks that severely reduces time remaining for analysis. Techniques that focus data extraction and knowledge acquisition in accordance with the probable value of the information might alleviate the analysts' burden. We envisage an effort that complements context-based enhancement of network analysis. We will capitalize on associated work in text mining that produces node/relation attributes (e.g., for socio-cultural and spatio-temporal information).

Concept Maps, or "Cmaps" (a self-referential example will be given in Section 2.1 and "tactical" examples in Section 3.3), with generalized graph structures and "arbitrary" labels, present problems beyond those of conventional structures used for inferencing. Their strength -- unlimited semantics -- appears initially to be a weakness from the

standpoint of computability. However, we are attempting in this project to make progress on this issue. To improve knowledge acquisition an intelligence tool should consider both the system's ability to readily address an analyst's question and the answer's influence of the answer on the analyst's specified main concern. A major intent of our effort is to develop algorithms leading to a system that reduces the "question answering" time spent establishing inferences. Such a system that reduces the number of propositional parameters an analyst must consider will likewise increase the efficiency of the analytical process: the system is to provide a reasoned prioritization of propositions for the user to address.

A decision maker is typically unable to quickly provide reliable estimates for all aspects of a situation. However, he or she can specify (say, via Cmaps) beforehand items the decision depends on. These depend on others in turn, and this configuration is specified as a network that propagates information. We wish to develop in mathematical terms the qualities that enable the next proposition to be explored when dealing with values in a concept network. We are investigating ways to express values in a Cmap in terms of both the utility of a consequent and the costs of obtaining antecedent information. Leading to a control strategy utilizable with mixed types of propositions, this work involves considerations of the value of information and derivation of influence.

This effort involves three related aspects: construction of tactical Cmaps; development of the analysis methodology; and feasibility assessment. We are exploring the use of Cmaps to describe tactical situations and facilitate military tactical decision making. Further, we intend to implement semi-automatic techniques for negotiating and updating military situational Cmaps by attempting to take into account influences and values of relationships among nodes. This latter objective is potentially of great value to the intelligence analyst in tailoring allocation of resources for knowledge acquisition (e.g., sensor allocation to obtain commander's critical information requirements) with knowledge of costs for achieving desired results.

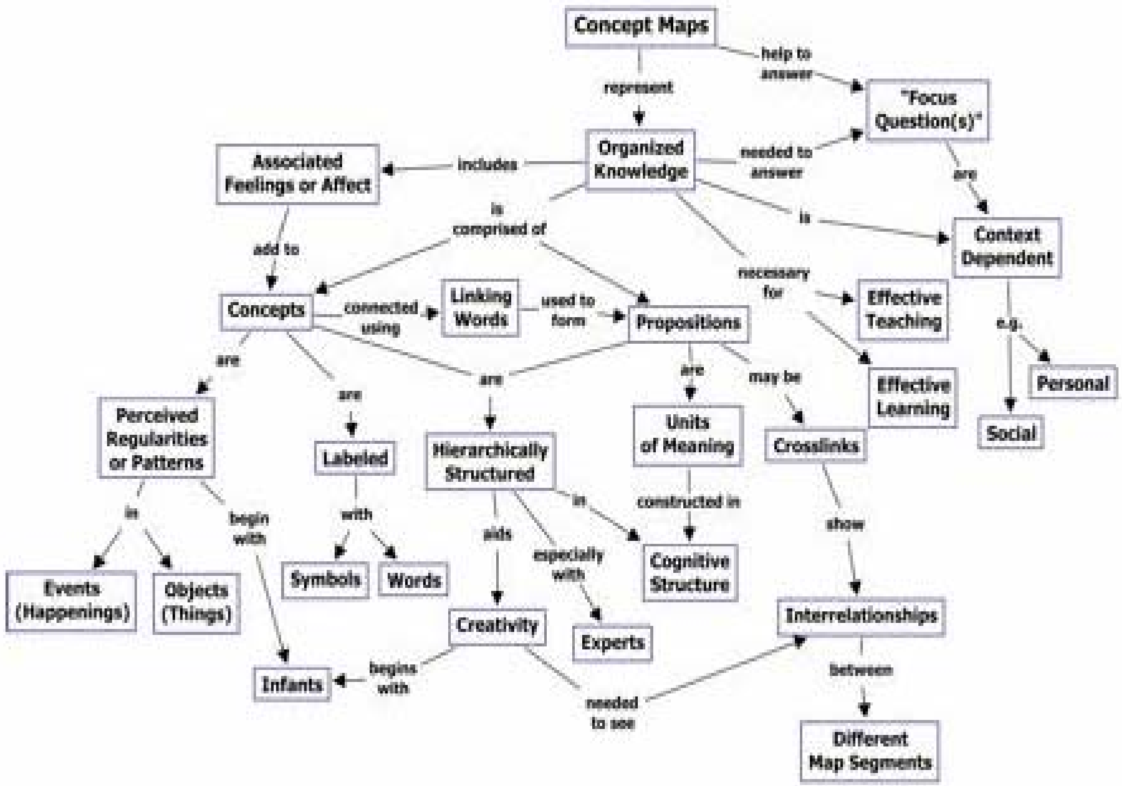
Our technical process involves application of team expertise to various subtasks, including: search for suitable cognitive mapping methods and flexible combat simulation; incorporation of social network analysis; output into development of a "scenario" (set of related concepts) for populating the map(s); development of mathematical algorithms for traversing a non-hierarchical array of linked nodes; development of one or more experiment(s) inclusive of metrics, to characterize the value of the prototype; implementation of improvements suggested through experimentation; final prototype evaluation; and testbed integration.

2. Concept Maps

2.1.Introduction

Cmaps are meaningful diagrams that express propositions <A, R, B>, where A and B are two concepts (or nodes) and R is a relation (or link) between them. Concepts are generally expressed as a few words within a rectangle. Relations are generally expressed

as a few words on a directional connector. Here is a Cmap about Cmaps. [Novak & Cañas 2006]



Cmapping is based on considerable research and a well-established theory of Meaningful Learning. [Novak & Cañas 2006; Ausubel et al 1978]. It has decades of application, primarily in education [Novak 1998], wherein Cmaps can be used to show gaps in student knowledge. At the other end of the proficiency scale, Cmaps made by domain experts tend to show high levels of agreement. [Hoffman et al 2000] Reviews of the literature and discussion of methods for making Cmaps can be found in [Cañas et al 2004] and [Crandall et al 2006].

The underlying principles are that humans understand in terms of such mental representations of inter-related concepts and that learning involves assimilation of new concepts and relations into existing propositional networks. The assimilation involves subsumption (i.e., including in a broader category or covering by a broader principle), differentiation (i.e., distinguishing, discrimination, or showing development of differences in by modification; not to be confused with the mathematical meanings to be discussed), and reconciliation (i.e., showing instances of consistency or compatibility). The learner, as he or she maps concepts from the more general and inclusive to the specific, has a method for creating powerful frameworks that enable utilization of the knowledge in new contexts.

Cmaps are a way to represent concept structures for decision making. Several types of such structures are used as formal knowledge representations: in particular, semantic networks. However, semantic networks and other forms are very different from Cmaps,

as will be made clear in the following discussion. Cmaps communicate knowledge in a form alternative to natural language, and help the user make associations and discover relationships intuitively. Moreover, additional informational resources can be integrated relatively easily through hyperlinking in the CmapTools software suite, which will also be discussed later. Cmaps are used in many domains world-wide to visually represent argument forms and knowledge structures.

In particular, Cmaps are being used within the intelligence community. They consolidate and summarize knowledge from various sources, and enable better presentations of overall knowledge structures. They facilitate thinking about complicated problems. A user can develop Cmaps for a domain of interest, link them with appropriate materials, and enable others to modify them. Networks of linked Cmaps can become very complex, particularly in an ongoing tactical situation. This project involves research into techniques for negotiating and updating Cmaps by accounting for values of relationships among the nodes.

2.2. Distinctions and utilities

Cmaps are different from other diagram types that express meaning by combining graph and text (for instance, semantic nets, cognitive maps, and mind maps). Differences involve syntax, dynamics, morphology, and semantics. Cmaps have an essential virtue of cross-links expressing relations across clusters of concepts. In real-world complex domains cross-links lend great power to understanding the “big picture” and have great potential for creative insights.

Several features are prototypical of Cmaps. A major one for our purposes is that of semi-hierarchical morphology. Many meaningful diagram schemes are based on centripetal or tree structures. However, Cmaps may be shaped generally like hierarchical shapes, with the more important concepts toward the top expressing context and more particular ones toward the bottom. The reader works downward through the levels expressing various relations. General concepts tend to be toward the top, subsumed concepts toward the bottom. Nodes toward the top provide context for details below.

The Cmap expresses interrelated concepts using propositions, and each node-link-node triad can be read “left to right” (in English) as a proposition. As a human-factors-based rule of thumb, a Cmap contains no more than five nodes under any given node. Importantly, a Cmap contains cross-links that show interrelation among concepts in different sub-domains of the knowledge structure.

In some types of diagrams links are unlabeled: associative graphs and semantic networks simply express that A is related to B, with path length indicating degree of relatedness or semantic similarity. For Cmaps, on the other hand, since the wording of nodes and links is essentially unrestricted, great expressive power is realized. However, this has been traditionally considered problematic with regard to computability. For instance, “Conceptual Graphs” are based on a link syntax involving a specific set of logical relations. [Sowa 1984] As will be seen, this notion also plays a role in “inference nets.” In Cmaps, the “is-a” link is but one relationship expressing “subsumption-

differentiation." Classification is a common form of link, but much more complicated ones such as "explains (with certainty 0.6)" are possible due to the unlimited semantics.

In Cmaps, distance between nodes does not connote semantic similarity or association value. Forcing that notion into Cmaps compromises their representational and expressive flexibility. Although closely-configured clusters lend human-readability to a Cmap, for our research the topology of a Cmap is more important.

Cmaps provide the cognitive flexibility needed to represent contemporary tactical knowledge that does not lend itself to conventional data structures. With Cmaps the user shows a subject in terms of linked nodes in a two-dimensional structure. Connecting arrows are labeled with phrases communicating the user's understanding of relationships among the concepts. A good Cmap shows the subject's "shape." Our research is furthering progress toward development of a tool to facilitate retrieval and updating activities depending on the data stored at each node.

3. Creating tactical knowledge models

3.1. CmapTools software suite

Although Cmaps can be made with pencil and paper or chalk boards, it is increasingly common to use computerized tools. Many academic or commercially available software packages are available to facilitate development of meaningful diagrams: KMap, SmartDraw, MindGenius, and so on. However, CmapTools is the package we are using for this project. The software, produced by the Institute of Human and Machine Cognition (IHMC), incorporates graphic primitives enabling users to construct and critique knowledge models. CmapTools is a publicly-available software suite for acquiring, constructing, and sharing knowledge. The tools permit a user to navigate to germane resources by enabling concepts to be linked to Cmaps, documents, images, Web pages, and so on. The software is well-developed (largely with DoD and NASA funding) and free for all Government uses.

CmapTools can be used as a stand-alone mode or as a Web-based service. The client-server CmapTools suite supports interactivity and collaboration, and facilitates sharing throughout the Web by converting Cmaps saved on CmapServers to browsable HTML. Automatic generation of pages and the ability to follow links to resources makes Cmapping a valuable mechanism to store and share knowledge. The interested reader is referred to [Cañas et al. 2004] for more information. However, this aspect of Cmapping is somewhat tangential to the topic at hand, and in most of the remaining discussion we will consider a Cmap as a self-contained entity.

The user interface of CmapTools allows straightforward construction (as well as browsing, modification, and linking) of a Cmap. The components (concepts and links) result from mouse clicks on the "canvas." Various style options are available according to the level of user sophistication.

3.2. Cmapping procedure

Cmapping is a skill that forces practitioners to strive for clarity about what the ideas they are attempting to express. Often one Cmapper facilitates the interview with the subject matter expert (SME); another captures the SME's statements into the Cmap. [Crandall et al. 2006]

Step 1. Cmapping starts with identification of a clear, explicit focus question to define the context and aid in expressing germane knowledge. The focus question can be an unattached node at the top of the Cmap space to orient subsequent discussion. Also, identifying the most important concepts for the higher levels of the Cmap may result in refining the question. The SME identifies five to ten general or important concepts in the topic. In multiword expressions often the words indicate separate concepts that can be pulled apart.

Step 2. Next the concepts are put into a holding area and then placed appropriately into the main space. Additional important concepts may be added.

Step 3. Concepts are linked with a word or short phrase defining relationships and resulting in propositions. Links should be precise, but can be categorized in many ways: "includes" is an example of classification; "requires" (dependency); "produces" (causal); "is known as" (nominal); "is a reason for" (explanatory); "is done by" (procedural); "rarely is" (probabilistic); "precedes" (event); etc. Once linking words and cross-links are identified, it is apparent almost every concept relates to many others, so the most useful links must be chosen. This observation factors into the notion of "merit," to be discussed shortly.

Step 4. The Cmap is refined by modifying, adding, and deleting nodes and links. Each triad is checked as forming a proposition. A concept's meaning is represented by all propositions linking the concept, so a given concept label is used only once in a Cmap. If a concept has more than five others linked under it, generally there is an intermediate level or latent concepts not yet expressed.

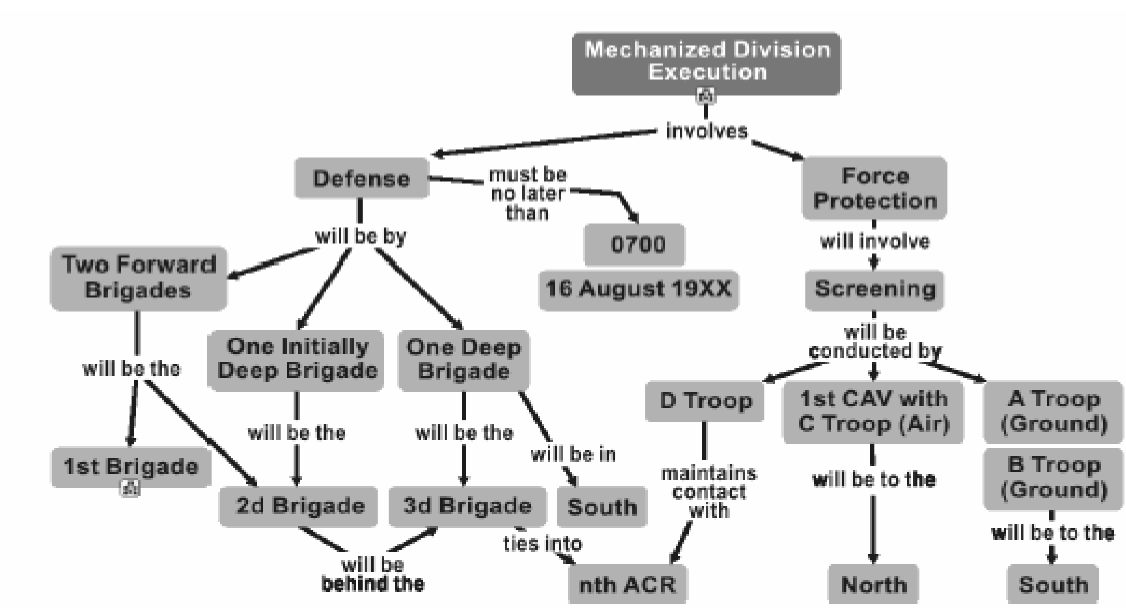
Step 5. The Cmapper looks for new relations and cross-links between concepts in different clusters and further refines the Cmap. The procedure may help elicit knowledge tacit in the SME.

Step 6. A set of Cmaps on a particular topic and hyperlinked together is a knowledge model. Such consolidation is performed, as is hyperlinking of resources (URLs, text, examples, video, etc.).

3.3. Examples

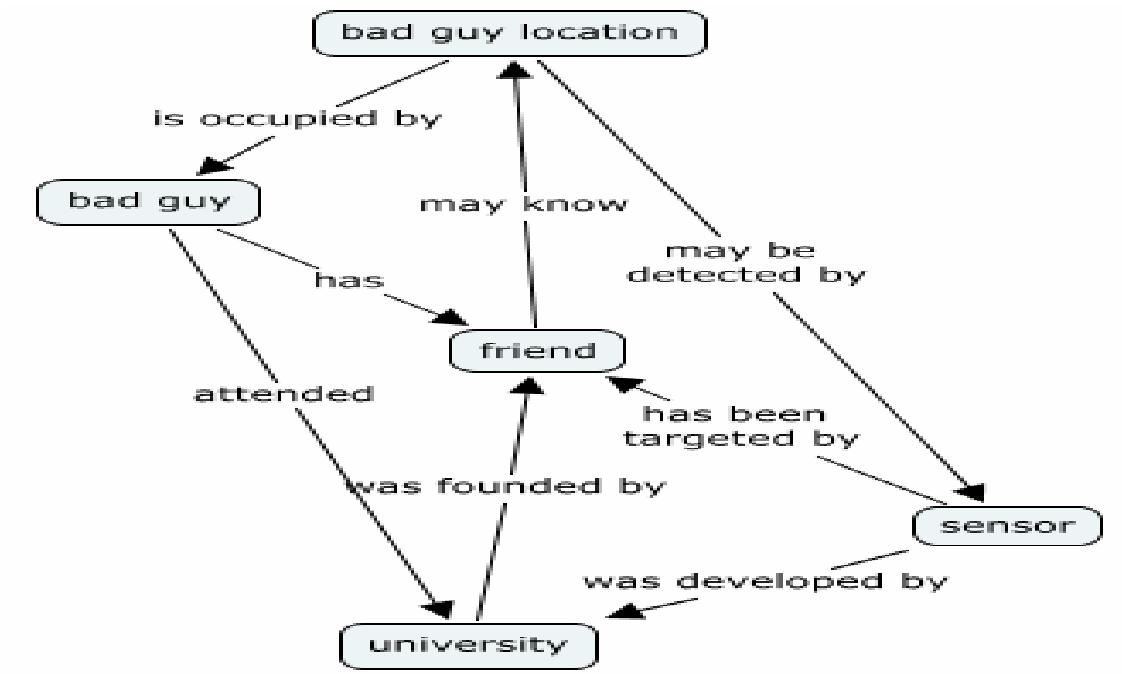
One inspiration for our effort is a contemporary proposal to modify the Army operation order (OPORD) process. [Hoffman & Shattuck 2006] The basic OPORD structure has been the same for over eighty years, with sections describing situation, mission, execution, service support, and command and signal. The basic OPORD development process is also relatively unchanged, and problematic in terms of both time and effort, since OPORDs can be quite lengthy. A proposed change to format and procedure involves the use of Cmaps, and would improve military planning and decision making. OPORDs may require cross-referencing among intent, mission, and goal, if only via expressed conditions. They may, contrary to guidelines, contain “anti-goals” and concerns. Such things lend themselves to Cmap expression, which further capitalizes on spatial proximity to facilitate observation of relationships among the ideas presented. Moreover, using our research, we hope to facilitate the pursuit of critical aspects within the concepts as the OPORD is being followed, thus improving execution monitoring and dynamic replanning. Studies have shown that experienced officers were considerably faster in searching for information using Cmaps rather than using traditional textual OPORDs. Cmaps can be set up as templates for planners, link to real-world resources, and expedite development by sharing throughout the chain of command.

Here is an example that suggests the level of detail needed to Cmap an OPORD. [Hoffman & Shattuck 2006] Although this diagram is perhaps not a Cmap in a pure sense, its construction uses the CmapTools suite, and as analysts become more familiar with the software and OPORD templates their usage of relational links should improve.



We have some Cmaps made in the intelligence area but could not vet versions for this paper. However, here is a contrived example that indicates a type of tactical Cmap entirely different from the OPORD application. Again, although not a well-developed

Cmap, it does help set the stage for the following discussions concerning influence, inference, and navigation.



4. Concept quantification and degree of influence

4.1. Propositional coherence

In a “propositionally coherent” Cmap, each node-link-node triad is a well-formed simple stand-alone meaningful expression. This moves Cmapping closer to enabling operations of propositional calculus (i.e., transformation rules on the space of syntactic expressions).

Diagrams that are meaningful to humans can also enable opportunistic computation. It is beyond the scope of this paper to discuss formal representation of phrase structures as in natural language processing. However, the difference between sentences and propositions is essential: we note that propositions may be tacitly contained in sentences. For instance, the sentence “My son plays with a red truck” contains four (Cmappable) propositions: I have (at least) one son (implied by the prepositional phrase), that son engages in play, that play is with a truck, that truck is red. [Hayes et al.]

Breaking a sentence into propositions may result in apparent “spawning” of concepts. However, it is seen they are in a sense embedded in the sentence; and this expansion can go on indefinitely in real world applications. We contend that propositional coherence is an importance step toward computability.

4.2. Description logic

IHMC researchers have discussed the notion of continuum of functional expression. [Hayes et al.] Propositionally coherent Cmaps ideally enable automatic consistency checking and inferencing. More sophisticated yet is a notion based on description logic: isolating logical patterns of quantification and redefining them as operators on a logical vocabulary for description and to form new relations. The description-logic style relates fairly naturally to Cmap notation and extends the idea of propositional coherence. Concepts can be separated into categories and statements relating them, for instance by asserting that a category is a subclass of another. Moreover, categories can be operated on by restricting a property to a particular value.

Classical formal logic permits relations among multiple arguments: for example, "performed (agent, action, time, place, circumstance)." Moreover, it permits binding of variables by quantifiers, thus augmenting the Cmap branching topology with the notion of recursion or scoping. IHMC has been experimenting with using a description logic to encode meanings using the Web-standard logical formalism Web Ontology Language (OWL). We note that OWL is being extended using logic programming, process-describing Petri nets, and if-then rules. [Hayes et al.] It is beyond the scope of this paper to discuss these efforts in detail. The point we are making is that human-interpretable diagrams can lead to expression of meaning in ways such that machines can draw logical conclusions from symbolic content, or in our case, guide information acquisition based on possible cost-effectiveness.

4.3. Influence

Some researchers in this area point out that adding a quantifier to a root concept makes it more specific, emphasizes the property of the concept that can change, and can lead to development of more dynamic propositions in Cmap construction. [Safayeni et al. 2003] A modification to the root concept affects selection of other concepts, based on the degree they affect or are affected by the change in the root concept property. Additional research is required to improve measurement of the dynamic components of a Cmap and to develop a measure of the degree of unity and interdependence of concepts in a Cmap. [Derbentseva et al. 2006] Our project of necessity involves such considerations.

Our work involves processes that are similar to forms of multi-criterion decision making. In both types of analysis, attributes must be operational, relevant, inclusive, and non-overlapping. Moreover, selection of the set of attributes cannot be separated from the actual search for attribute values and subsequent analysis. The "quantities" of a tactical Cmap to be traversed are generally incommensurable; trying to assess influence on a consequent linked in grammatical or qualitative ways to disparate antecedents is problematic. For example, in the OPORD CMap, "Defense" is influenced by actors and time. Along these lines, attributes often involve intangibles (such as emotional states) that must be properly considered to avoid distortion of the analysis. Part of our research is development of logical and computationally feasible ways to incorporate intangibles. In

many representations we must reflect uncertainty, if only with regard to the evaluation of an action on an attribute.

For assessing degree of influence, we take as a starting point the natural language structure of English. For example, setting aside for now any "measurement," we note that an adjective has influence on its noun by qualifying or quantifying it. Similarly, an adverb modifies a verb. A different sort of influence is the subject-verb-object construct. Yet another involves the prepositional phrase (e.g., trees are green *during summer*). This can be taken in another direction by a quantifier: some trees are green. We note that earlier IHMC research [Reichherzer et al. 1998] has considered article, quantifier, cardinal, noun, adjective, adverb, verb, auxiliary, modal, preposition, noun, negation as denoting classes of words.

As indicated earlier, Cmap propositions comprise a left concept, a link, and a right concept. By utilizing keywords we can somewhat characterize both the concepts and the linkage. For instance, quantifiers or adjectives can modify the left concept, and adverbs can modify the linkage. Verbs can also denote dependencies among concepts. Another consideration is the voice of the proposition: in active (passive) proposition the active component is the left (right) concept, and this is important in application of the notion of transitivity, to be considered shortly. We may apply if-then deductive reasoning as one sort of measure; another may be based on looking for identical concepts, links, or keywords.

5. Inference net considerations

5.1. Introduction

Computerized expert consultant systems have traditionally utilized representations of graphs known as inference nets. In this construct, nodes represent facts or propositions describing germane parameters. Each link represents a mathematical function or rule that produces a consequent proposition from antecedents: the value of a consequent is inferred from values of antecedents. Facts are related in an order: the links define implications that enable the network to "propagate" information (e.g., the probability of proposition authenticity). A proposition's value, which may change, is developed by applying the function to the values of the direct antecedent(s). Propagation is a sequence of such "assignments" that proceeds from some datum though all direct and indirect consequents. Conventionally, a fact is developed by one kind of assignment function. However, there is no problem with a fact having multiple antecedents or with a fact being associated with a consequent in more than one way. Also, inference net structures are acyclic to avoid infinite loops; but (limited) cycles can be accommodated. [Slagle & Koniver 1971] Expansions of these notions and development of techniques to handle a variety of topologies are essential aspects of our research.

5.2. Navigation and updating

A central aspect of the solution of Cmap navigation, proposition prioritization, involves using derivatives for describing degree of influence of an antecedent on a consequent. When we quantify influence with functions of real numbers the "conventional" calculus becomes applicable. However, even when considering the derivative as a slope (that is, the difference between the functional values divided by the distance between the basis points), it is apparent that the nature of the conceptual data set being considered makes a difference with regard to differential formulation and computation.

A network typically contains consequents that do not imply anything else, that is, that are the subjects of the evaluation. A complicated problem is that competing hypotheses may require multiple such top propositions, which in general have a mixture of antecedents, some in common and some specific to each top proposition. Also, some propositions are "askable" in the sense that the user might be able to supply the information; and we may consider a degree of askability, for instance related to the user's experience. Top propositions are generally unaskable, and when the user provides information to askable propositions "lower" in the network, that information is propagated toward the top.

A common method for updating the top propositions is reverse chaining of the links in a depth-first traversal. A consequent is "expanded" to its antecedent(s), and if the user can update an askable parameter the information is propagated and the traversal continues. This can be time consuming; a more intelligent system would consider the most relevant parameters first. Development of mechanisms to choose such questions was the goal of earlier research and resulted in a technique, discussed in the next section, for a best-first strategy to traverse inference networks. [Slagle & Halpern 1982] The most important questions are asked first, and when there is no chance of significantly changing the top proposition, questioning ends. This technique can be applied to a link expressible as a differentiable function. A significant portion of the ongoing work is investigation of ways in which it can be extended into the realm of Cmapping.

5.3. Merit

The "merit" of a node may be considered as the absolute value of change in the probability of truth of the top proposition divided by the cost of expanding the untried proposition. A small merit value represents that expansion of the node will have little influence on top-level probabilities, that expansion will be enabled only with large cost, or both; large merit indicates that a proposition is cost-effective with regard to its influence on the top node. Note that although we speak here for initial development in terms of probability, the measurement of influence is actually more complicated and abstract, as discussions in Section 4.3 have indicated. In this spirit, we will use the term "benefit" in some subsequent expositions.

Some applicable mathematics, which will be transformed by analogy shortly, involves the differential calculus, based on the notion of rate of change. With functions of several variables we measure the rate of change in various directions. Specifying the directions as

the positive coordinate axes, the resulting partial derivatives are of fundamental interest. In particular, we define the partial derivatives of a function f at a point $p_0 = (x_0, y_0)$ by $\frac{\delta f}{\delta x}(p_0) = \lim_{h \to 0} \frac{f(x_0 + h, y_0) - f(x_0, y_0)}{h}$ and $\frac{\delta f}{\delta y}(p_0) = \lim_{h \to 0} \frac{f(x_0, y_0 + h) - f(x_0, y_0)}{h}$.

That is, we calculate the partial derivative with respect to one coordinate variable by holding the others constant and differentiating the resulting one-function variable. We note that "holding y constant" can be interpreted geometrically as taking a cross-section of the graph of f in the plane $y = y_0$, so that the value of the partial is seen to be the slope of the tangent to the cross-sectional curve. A partial derivative of a numerical-valued function of several variables is itself such a function, and the result of a succession of partial differentiations on a (sufficiently smooth) function of several variables is independent of the order.

We now set forth (with neither derivation nor technical stringency; the interested reader is referred to [Lang 1987]) a general form of the so-called chain rule. For functions of one variable the rule for differentiating a composite is relatively simple: for $w(u(x))$ we have $\frac{dw}{dx} = \frac{dw}{du}\frac{du}{dx}$. A function is continuously differentiable if it is continuous and has continuous first partial derivatives. Now let w be a continuously differentiable function of $u_1, u_2, \ldots, u_n$ and let each u_i be a continuously differentiable function of the variables $x_1, x_2, \ldots, x_m$. Then w is a continuously differentiable function of $x_1, x_2, \ldots, x_m$ and $\frac{\delta w}{\delta x_j} = \frac{\delta w}{\delta u_1}\frac{\delta u_1}{\delta x_j} + \frac{\delta w}{\delta u_2}\frac{\delta u_2}{\delta x_j} + \ldots + \frac{\delta w}{\delta u_n}\frac{\delta u_n}{\delta x_j}$.

We can represent merit as a partial derivative. Consider a (top) node A with subnodes A_i, $i = 1, \ldots, n$. A subnode A_i may have its own subnodes A_{ij}, $j = 1, \ldots, m$. Now the merit of an untried proposition can be expressed as $\left| \frac{\delta B}{\delta C_{ij\ldots z}} \right|$, where the numerator represents the change in benefit (or probability) of A and the denominator the cost of expanding the untried subnode $A_{ij\ldots z}$. Further, applying the chain rule results in $\left| \frac{\delta B}{\delta C_{ij\ldots z}} \right| = \left| \frac{\delta B}{\delta B_i} * \frac{\delta B_i}{\delta B_{ij}} * \ldots * \frac{\delta B_{ij\ldots y}}{\delta B_{ij\ldots yz}} * \frac{\delta B_{ij\ldots z}}{\delta C_{ij\ldots z}} \right|$, where the final factor is the only one expressing the cost of expanding the untried node. This "self-merit" represents expected change in the subnode's value with respect to calculating the value or expanding the traversal to the antecedents – in other words, it reflects change in probability per unit cost of expanding the subnode. Self-merit is generally estimated by the opinion of a subject matter expert; in our case, an intelligence analyst dealing with the specific situation portrayed in the Cmap considers self-merits as part of the problem.

Note that the other factors in this equation represent the influence of change in benefit of a subnode on the benefit of the next-highest node. Each antecedent-consequent pair has such a “link-merit,” representing the degree of influence an antecedent has on a consequent. A portion of our effort in this project involves calculations of derivatives (or symbolic representations of derivatives) of functions used in the updating procedure of the preceding section.

In an inference net traversal using this scheme, the untried or unexpanded proposition node with the greatest merit has the largest potential to influence the top node; the system disregards alternatives with less promise. It is this notion that we hope will aid the analyst trying to decide avenues of investigation or the commander concentrating on subcomponents of an OPORD.

In cases in which several top nodes exist, we might consider the most meritorious node as the proposition with the highest merit in any of the networks emanating from the top nodes. In effect, we create an artificial node higher than the existing top nodes, and set forth a requirement that all top nodes be evaluated in similar units, a notion that is under investigation. This is analogous to the focus question that guides the formation of a Cmap in the first place.

We note also that the merit mechanism examines merits from the entire net, not just a set with a common consequent. Therefore this produces fewer questions than would result from a depth-first algorithm. Although the best-first methodology may jump around the net, the time and effort saved will mitigate any perceived disadvantage. Also, the best-first methodology allows for a natural freedom to alter cutoff values, since all nodes are reconsidered each time a question is asked, whereas in a depth-first strategy changes to the cutoff apply only to non-traversed parts of the tree.

The designer of such a system should not have to develop merit functions; he or she, as SME, would provide nodes, along with self-merits and mathematically-compatible links and self-merits, which must be “correct” relative to each other. A node whose benefit may (not) change much or whose parameters are (not) easily specified has a high (low) self-merit; questions that are more difficult to provide inputs for (e.g., requiring large amounts of data or calculations) are more costly. We intend to pursue implementation in software after the foundational aspects of our research are sufficiently developed.

In summary, merits enable consequent propositions to be readily updated. Self-merit is expected change in a proposition divided by the cost of expanding the proposition. Link-merits portray by mathematical functions the capability of an inference rule to alter a consequent. A node’s total merit is computed by multiplying its self-merit by the link-merits of all links directed from the node to a top node. Selecting the most meritorious proposition to deal with at any time is a reasonable way to “navigate” the net, since the merit measures the cost-effectiveness of a proposition to modify the top proposition. Linking functions in a general inference net will express rules for updating propositions with plausibilities expressed in a variety of ways. However, merit formulas will be found with the same method: the differentiation discussed earlier. Moreover, we note that

previous researchers attempted to develop an algorithm for handling nets in which the links or nodes contain variables. [Slagle & Koniver 1971]

We now move our discussion into the realm of Cmaps.

6. Transition to Cmaps

6.1. Introduction

Note that significant differences exist between inference networks and Cmaps. In particular, Cmaps are designed to have cross-links that complicate the propagation of information. Indeed, the meaning of such propagation is subject to new interpretation, since the nodes in Cmaps are concepts, not propositions; the propositions in Cmaps are expressed as node-link-node triads. We believe (at least) two avenues of investigation present themselves: transform "germane" (where this technical notion is a research topic) triads into net-inferencable "propositions;" or consider the Cmap structure as an inference net in its own right. Our current research concentrates on the second notion. However, we believe from initial investigations that a hybrid approach will probably be necessary for Cmaps involving real-world tactical intelligence.

6.2. Cmap link-merits

We now consider calculation of special link-merits that are germane to our problem. Commonly-used links include: are, at least, at most, can be, cannot be, different from, exact opposite of, exactly, is a, must be. We will not dwell on calculation details here but rather sketch how results may be derived. By way of illustration, let us consider the logical "and" link, in which the truth of a consequent depends on verifying all its antecedents. We will write the benefit of an antecedent E_i as estimated by a user as $B(E_i \mid E_i')$, where E_i' represents the evidence or observations on which it is based. Assuming antecedents are independent, we can write the benefit of a consequent $B(C \mid E_1', \ldots E_n') = B(E_1 \mid E_1') * \ldots * B(E_n \mid E_n')$, where we treat "benefit" as "probability" in the sense that the benefit of the consequent, given the present benefit of each antecedent, is the product of all current antecedent probabilities. Now the link-merit of the consequent with respect to any antecedent is found by computing the partial derivative of the consequent benefit with respect to the benefit of that antecedent:
$\dfrac{\delta B(C \mid E_1', \ldots E_n')}{\delta B(E_i \mid E_i')} = \dfrac{B(C \mid E_1', \ldots E_n')}{B(E_i \mid E_i')}$. [Slagle & Halpern 1982]

As we have mentioned, in many inference nets an antecedent node may have several consequents. This presents problems in backing up merits that have been discussed at some length. Earlier researchers observed that practicality tends to dictate ignoring the problem caused by nodes with several consequents. [Slagle & Halpern 1982] This observation can be taken at face value in the current project: that is, we can "simply" consider any Cmap in terms of its directed-graph component an "inference net" and

proceed. However, we believe there is more to solving the problems of multiply-connected nets, and ongoing investigations involve sketching possible methods.

6.3. Dynamic Cmaps

Several major steps have arisen in the evolution of Cmaps. [Hoffman et al.] The first was development of the CmapTools suite of user-friendly graphical tools to support creation and sharing of Cmaps. The second was the realization that hyperlink-tagging nodes to multimedia resources enables Cmaps to preserve knowledge and serve as interfaces for Web work. A third was that Cmap knowledge models could be interfaces to knowledge-based systems, such as expert system explanation components. A fourth major step is: Cmaps that can "do things."

Such Cmaps might be "dynamic" in several ways. For instance, animation (e.g., flashing nodes) can express the "process-like" nature of a representation. Other aspects include using Cmaps to: represent events or processes; invoke or perform procedures; pull data files into software for operations; and help configure tasks for software agents. A capability germane to our project is the notion of having nodes or links change as the result of an operation performed on newly acquired data. In such data-driven mutation, after the transformational states of a process have been performed, the Cmap itself changes to represent the new informational structures created by the process.

Several innovations required for realizing such dynamicisms are discussed in detail elsewhere. [Hoffman et al.] For our project, we are most concerned with the notions of "propositional coherence" and "nested node." Propositional coherence has been discussed earlier in this paper. A nested node does not present an individual concept, but rather is a place holder for a cluster of concepts and their relations. It allows one to say "these nodes are different from those nodes, in some respect" and thus suggests a scoping mechanism, taking Cmapping closer to enabling the operations of predicate calculus (i.e., deduction extending propositional calculus).

Other researchers have investigated Cmap structure as a means to encourage dynamic representation. Along these lines, we can dichotomize conceptual relationships into static, which reduce uncertainty in the labels, and dynamic, which handle with co-variation among the concepts. Hierarchies and classifications, dealing with composition and belonging, are usually set forth in static relationships. Dynamic relationships emphasize how change in the "quality" of one concept results in a quality change of the other in a proposition. [Safayeni et al. 2003] This notion can be amplified by the link-merit and information propagation mechanisms just discussed: incorporation of ideas concerning rate of influence into this context is, we believe, new work. Dynamic relationships among concepts can be poorly formulated, making them difficult to express mathematically. [Derbentseva et al. 2004] Indeed, that is also part of our research: assessment of the degree to which dynamic concepts can be represented either numerically or symbolically.

One researcher has proposed the notion of cyclic Cmaps, extending traditional semi-hierarchical Cmaps, as a means to facilitate representation of dynamic thinking. [Safayeni

et al. 2003] The cyclic Cmap connects all concepts in a loop with one input and one output each, so that changing the quality of any concept affects all the others. Moreover, we note that qualification or quantification of a concept restricts its set of potential meanings and emphasizes a specific property of the concept that can change its value. An extending aspect of our research involves the fact that in real-world tactical Cmaps multiple dynamic properties will have to be handled.

7. Conclusions

The objective of this nascent research is to develop methodologies for applying Cmapping to decision-making analysis within military scenarios. They will provide a vehicle useful both for research in information mediation and for capturing real-world information to be processed by other data fusion techniques. The concepts we are examining are currently rated using the Technology Readiness Level scale as level 2; our research will advance the state of transferable developments to level 5. Resulting computer tools will eventually be reviewed by several SMEs for applicability to the military decision making process (MDMP), specifically the intelligence analysis portion.

The Army co-authors have obtained software and training from IHMC. They have obtained a training scenario from Army sources with a decision set and a solution set. Cmaps have been created to represent the scenario decision set, and we are exploring utility of our evolving algorithms within the MDMP. This is not a totally new start; we are capitalizing on earlier work that Cmapped terrain analysis and military OPORDs. We are in the process of converting (portions of) Exercise OPORDs and scenario databases into Cmaps for studying the implementation and repercussions of our research.

Propositional/predicate calculus efforts and mutation techniques are germane to the current project. In particular, the notions of combining sets of node-link-node triads into composites and of analyzing node-link-node components are of potential value to military intelligence applications of Cmaps. However, we are also exploring formalisms associated with the “degree of influence/applicability” and the cost/benefit of node expansion that associates quantitative information to concepts and links.

We note that this work may lead to a kind of alternative to the probability manipulations of Bayesian belief nets and measures of certainty – an approach that keeps the mathematics tied to meaning. We also hope that higher-level considerations of the way in which human-machine teams fuse information or knowledge might result. It is hoped that some of the approaches we are considering will prove fruitful in advancing the cause of cognitive multipliers for both the analyst and the commander.

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